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# REACH OUT AND TOUCH SOMEONE: CONTROLLING HAPTIC MANIPULATORS NEAR AND FAR

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Abstract: Robotic devices now commonly interact physically with humans. Control issues surrounding this constraint are discussed and several approaches are considered. Examined in detail is the use of energetically passive designs, especially of the dissipative variety. Three different control algorithms are introduced and compared in their ability to guide a human user along a desired path in a rapid fashion. Physical measurements are correlated with user opinion. Other human-computer issues that are introduced in this paper are time delay for force reflective manipulation haptics for equipment operation and a robotic surface with many degrees of freedom. 

Keywords: user interface, robot control, passive, velocity control.

## 1. INTRODUCTION

The old rule that robots and people must live in segregated workspaces is being replaced by intimate physical cooperation between the two. "Robots" as used here will be defined broadly. The motivations vary, but include providing improved feedback to the user on operations in remote environments, intuitive display of virtual or synthetic environments, situations where the human is the work piece (surgery or rehabilitation), and enhancement of physical manipulation performed with the aid of human intelligence. These tasks may be local or distant, implying a variety of communication channels and communication delays. Clearly, the need for improved control in this new world of human-robot intimacy is of utmost importance and has brought about new approaches that will be presented here.

Since historically the major concern for shared human/robot workspaces has been safety, our initial discussion will revolve around that subject. In certain cases there are inherently safe technologies that have been recently developed. After that, a brief discussion will cover the enhancements that are possible in teleoperation by concentrating on the interaction at the teleoperation master. System stability and effectiveness can be improved even when the remote system is limited in its controllable behavior. This is of great practical advantage where the remote system may be a large, high power system and precise control is extremely difficult. An extension of this interest is the case with significant communication delays between the slave robot and the force-reflecting (more fashionably termed haptic) master. Our results show that even with globe encircling distances over the Internet, dramatic improvements in manipulation performance are possible. Finally, we will present a more futuristic concept now being reduced to practice: digital clay. Digital clay is a surface controlled with a large number of actuators for the purpose of shape input, shape display and haptic interaction. The concept will be presented and the initial control aspects will be explored. This is done only briefly as a submitted paper on this subject appears in this conference as well.

Because of space limitations this paper, the written version of a plenary talk, will not be able to fully explore all these areas in great detail. Rather than be equally brief on all areas, this paper presents a discussion of passive haptic devices in some detail, while treating two other areas with extremely little detail. The justification is that the most detail is given to the newest work, not otherwise presented here. The other topics are better documented in other papers as will be referenced.

## 2.0 SAFETY THROUGH PASSIVITY

The concern for human safety dominates the interaction between human and machine. Haptics inherently involves imparting forces to the human user to convey information about the task at hand. Force response of the manipulator is as important as the response of the human, however. Response to force creates a feedback loop that has widely varying gains depending on the stiffness of the environment, in this case a human. The gain of this feedback loop can be responsible for instability if the control system is too aggressive. The aggressive behavior though is needed for the best performance. The perfect haptic manipulator must also respond with highly varying sensitivity to meet the need ranging from fast, unimpeded motion that may suddenly change to represent collision with a stiff wall. The transparency and stiffness is a valuable measure of the ability of success of a haptic design.

The possibility of an autonomous robot colliding with a human that has moved into the path of motion requires some form of sensing, such as proximity or vision. This is clearly a concern for the traditional industrial robot if the workspace is to be shared with a human worker but not the issue confronted here. This may be viewed as a flaw in programming of the human worker. Another aspect of safety is the reliability of the hardware and software implementing the robot. Given that the reliability will never be perfect, alternative strategies for fail-safe operation are needed.

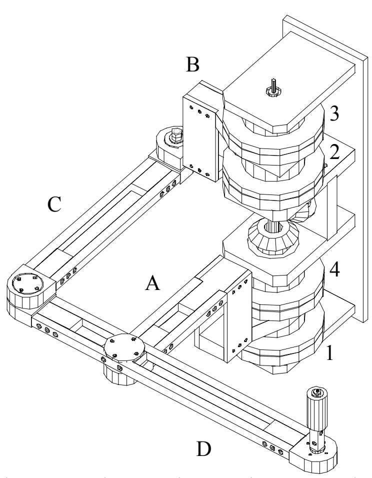


Figure 1 The Passive Trajectory Enhancing Robot (PTER)

### *2.1 Passively Actuated Robotic Devices.*

Physical damage can result from an energetic blow to a robust user or from a minor blow to a fragile user or patient. For example, exercise machines are one interesting form of haptic device. A robust user can exert high forces that should be resisted by the exercise machine during strength training. For cardiovascular conditioning, and exercising “fast twitch” muscle fibres, low force high-speed motions are preferable. If you want to do these two exercises with the same machine you will have the potential of high power delivered to the user, i.e. the product of velocity and force, if the machine is an active machine. Such a machine was developed in the late 70’s by the author and his colleagues (Book *et al.* 1974) . While delivering the greatest flexibility, this machine also had a great potential for injuring the user. It is also possible to have high forces and high speeds from an energetically passive machine. However, the forces and velocity are now constrained so that power flow is on the average in only one direction. In exercise terminology this allows only concentric (the muscle is doing positive work) and not eccentric exercise where work is done on the muscle. Some trainers want to have both exercise modes. On the other hand, for computer-assisted surgery, a low energy blow might cause severe consequences.

In applications such as this it may be preferable to use an energetically passive device. More specifically, whenever the user is able to directly power the motion and the robotic aspect of function is to modulate in some way his motion, passive robotics may be a safer solution. This could include the use of haptic masters and synergistic devices where trajectory enhancement is the goal of the manipulator. Several such devices have been designed. The dissipative passive device at Georgia Tech is called Passive, Trajectory Enhancing Robot (PTER) and will be described in some detail below. Colgate and Peshkin (Colgate *et al., 1996)* have created and championed the Cobot device and built several versions of it. This nonholonomic device inherently is a single degree of freedom device in a local sense, but by steering the direction of motion can be selected. The concept has been implemented in a planar vehicle form called Scooter and as a 3R arm (Moore *et al.,* 1999) where the steering aspect is implemented on a continuously variable transmission. The Cobot does not need to incorporate much dissipation and hence is well suited for path following but must sense and quickly respond to user force direction to enable free motion. A third type of device is known as PaDyC (Schneider, *et al.* 2000) conceived by Troccaz and colleagues for medical applications. This device is speed limited to operate between two maximum joint speeds, one in each direction, by two motors per joint and a clutching mechanism. The motors do not deliver power to the robot but only determine the speed at which the clutch is engaged. This concept has been proposed for a six dof device targeted for delicate cardiac procedure of needle insertion. Since velocity limitation is the natural constraint for PaDyC, computer control of these limits is required to enforce position constraints.

The device used at Georgia Tech is the Passive, Trajectory Enhancing Robot (PTER) shown in Figure 1. This five bar linkage design uses four brake/clutches labelled 1 through 4 in the figure. Two clutches couple links A and B to the base, whereas one clutch couples A to B and another couples A inversely to B. As a consequence there are four lines at any point called single degree of freedom lines defined by locked clutches and increased pressure between the plates of one clutch shifts the motion more closely to that direction. Since the control action puts no energy into the system, and to the contrary always removes energy from the system this is called a dissipative haptic display. PTER is ideally suited in two degrees of freedom to permit unfettered motion in the permissible workspace but restricting access to an arbitrarily defined space that for any reason may be off limits.

Other dissipative devices have been developed by other researchers. Matsuoka and Miller have designed a large three degree-of-freedom interface using magnetic particle brakes (Matsuoka and Miller, 1999). This device has one prismatic and two spherical joints. It has been used to study the feasibility of producing virtual environments (haptic effects) with a passive device, to model virtual walls in the workspace, and as a patient rehabilitation device.(Matsuoka and Townsend, 2000; Matsuoka and Miller, 1999). (Sakaguchi and Furusho, 1999) at Osaka University have developed a two degree-of-freedom device kinematically similar to PTER, but which uses motorized electrorheological clutches. These clutches use a fluid coupling which changes viscosity with applied electric field. By modulating the viscosity, the amount of torque transferred between plates of the clutch may be controlled. This device is active, but a passive ER clutch is currently under development by colleagues of that author with the intention of using it as an actuator in a haptic interface. Will, Crane, and Adsit at the University of Florida have developed a six-degree-of freedom hand manipulator that uses magnetic particle brakes as actuators (Will and Adsit, 1995). Tajima, Fujie, and Kanade at Hitachi, Ltd., Japan, have proposed PALM-V2, a surgical tool positioning mechanism that uses variable dampers to provide resistance to motion (Tajima *et al.*, 1997). Both of these devices are dissipative.

### *2.2 Control of PTER*

A variety of control algorithms have been considered. For example, by locking one or the other clutch the motion will rapidly align with one of the single degree of freedom lines. This allows one to slip along a forbidden region with little dissipation, passing through a number of these single degree of freedom lines as shown in Figure 2. Alternatively, a continuous variation in the clutch actuation is used in the velocity-based controller shown in Figure 3.

In either case, outside the region of influence of the obstacle, the user is free to move arbitrarily. Near the object, the user cannot move arbitrarily but will be diverted around the object in spite of the direction of applied forces as shown in the two previous figures. In spite of the potential for more closely approximating the object's boundary in the velocity controller, the user clearly felt that the SDOF controller was somehow better.

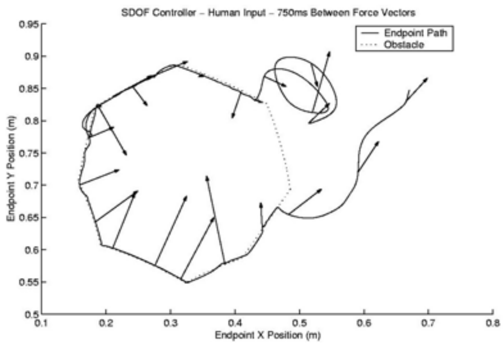


Figure 2 Single Degree of Freedom Controller

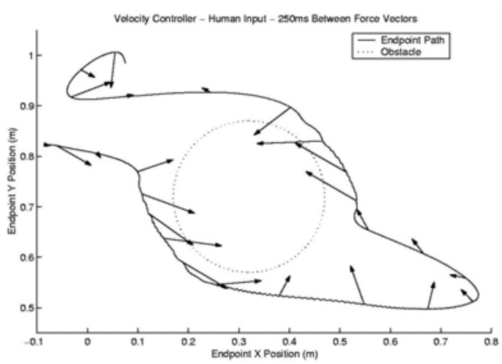


Figure 3 Velocity Ratio Controller

The difficulty in reducing the user "feel" to a measurable quantity is one of the frustrations of the designer of user interface devices. In our case with PTER, a priority was given to controlled experiments relating this subjective evaluation to measurable quantities. It was done for a different task, the trajectory following path. In this task the user must move rapidly from a start box to a finish box along a predefined path. Controllers of several varieties similar to the velocity controller for obstacle avoidance were used. Figure 4 and Figure 5 will give an image of the improvement of using the trajectory-enhancing controller compared to the uncontrolled case. The desired trajectory is shown in the heavy solid line. But how did the different controllers "feel" to the user? As we seek to make the job easier for the user to perform successfully, do we increase the operator workload?

To answer these questions, Swanson (Swanson, 2003) conducted surveys of the users to compare with the measured data such as accuracy, speed, acceleration, jerk and acceleration and jerk at high frequencies. The standard NASA Task Load Index (TLX) (NASA Ames Research Center) was used in the survey. First we note that for four of the controllers the statistical results support at the 95% confidence level that path error can be reduced while not reducing speed as shown by comparing the uncontrolled path error to the path error for several controllers and the path speed for the same controllers as shown in Figure 6 and Figure 7. with the controller names contained in Table 1.

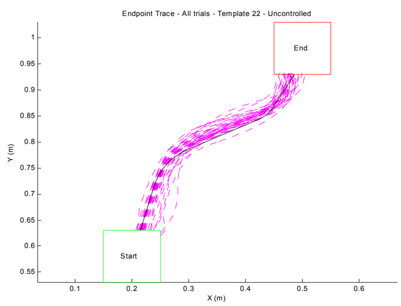


Figure 4 Track of End Point for Uncontrolled Motion.

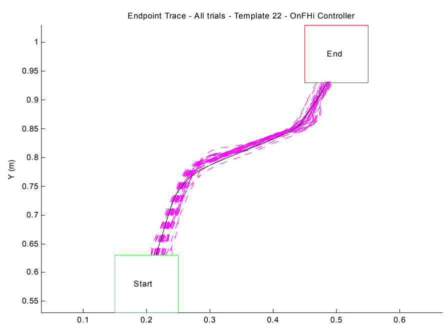


Figure 5 Track of End Point for Controlled Motion.

Table 1 Controller Abbreviations.

| Abbreviation | Controller |
|---|---|
| NoCon | None |
| VL | Velocity ratio low gain |
| VH | Velocity ratio high gain |
| VCL | Velocity ratio, coupling, low gain |
| VCHi | Velocity ratio, coupling, high gain |
| OnFLo | Optimal without force measurement, low gain |
| OnFHi | Optimal without force measurement, high gain |
| OFLo | Optimal with force measurement, low gain |
| OFHi | Optimal with force measurement, high gain |

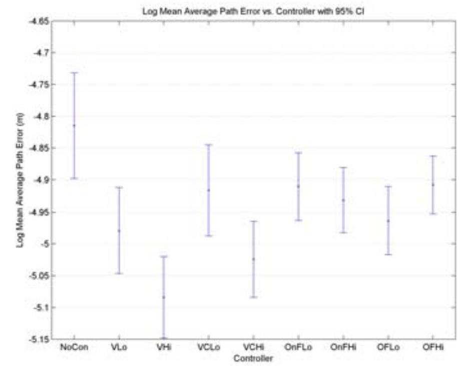


Figure 6 Statistics of Improvement in Accuracy

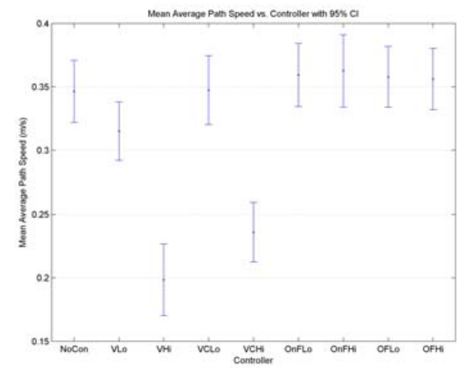


Figure 7 Statistics of Speed of Motion

The users felt more heavily worked when the average force they had to exert was high as shown below in Figure 8. Smoothness, a key judgment related to the positive attitude toward the device was highly correlated with the spectrum of acceleration and jerk. This is shown by the correlation trends in Figure 9 (jerk is similar). As a result of these experiments we have shown that the dissipative passive haptic device is effective for the path following task and better understand how to relate user perception to physically measurable quantities. Now more needs to be said about the controllers themselves and the quirks of controlling a braked device.

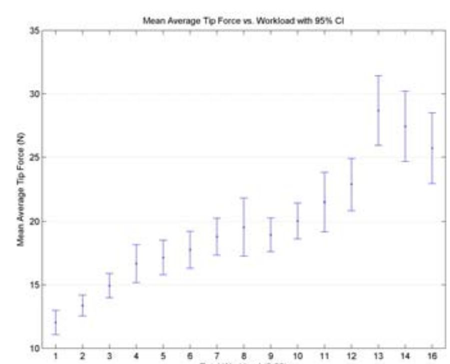


Figure 8 Correlation Between Perceived Workload and Force

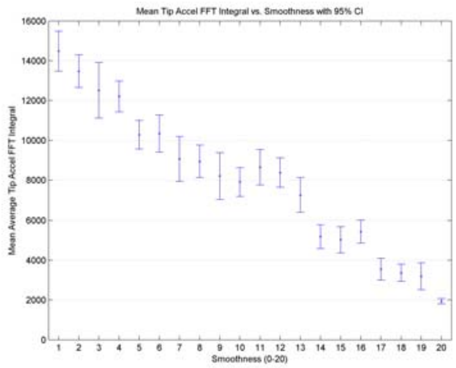


Figure 9 Correlation Between Perceived Smoothness and Acceleration

*2.3 Controllers Suitable for PTER*

Actuation of any passive device is limited by the sign of the change of power. This is true for the system overall and also for any passive actuator which is used to induce a change in velocity. Since PTER has four clutches for controlling two degrees of freedom, additional capabilities are provided that must be utilized. These clutches are electromagnetically actuated friction clutches that have a number of unpleasant characteristics such as finite clearance and Coulomb friction behavior.

For path following, the specification of the desired path depends on a predefined line in space (a plane for present purposes) and determination of a direction to move along that line. Since error between the actual position and desired position is expected, a velocity field is determined at a high level to reduce that error. This field is perpendicular to the path when far off course and curves to be tangent to the desired path. This velocity field, transformed to joint space desired link velocities by the inverse Jacobian, is used by a low level controller when determining the actuation signals.

Several methods of control have been tried for the low level controller: (1) velocity ratio control, (2) velocity ratio control with coupling elements and (3) optimal control. In addition these controllers have been implemented with and without sensing the force applied by the user and with two sets of gains. Force sensing is most useful if it becomes necessary to stop the user all together since he or she is moving strictly away from the line. The user can reverse the applied force to move toward the line and then the arm must be unlocked and allowed to move again. If force sensing is not incorporated this correction cannot be noticed and the arm will remain locked. A number of other practical issues such as filtering the position measurements are important to the total implementation and are described in (Swanson, 2003) and (Swanson and Book, 2003).

The velocity ratio controller uses only two of the actuators. It computes the ratio of desired to actual velocity for the two links connected to the base. Note that the ratio of these values, not the absolute value is important to determine the direction. The smaller of these two ratios, call it $c_n$, indicates that this joint must be slowed down. If both ratios are the same, the direction of motion is perfect. The velocity ratio controller applies a control action to the one actuator of $u=K(c_{max} - c_n)$ with the other actuator left untouched.

The velocity ratio with coupling elements checks to see if the direct or inverse coupling clutches would have a desired effect on both joint angular velocities. One velocity will speed up only if the others slow down. If one of the two coupling actuators has this effect it will be used, thus reducing the amount of kinetic energy removed from the system. Otherwise, this controller lapses back to the previous one.

The optimal controller seeks to use the actuators that minimize the instantaneous loss of kinetic energy combined with a weighting factor with the angle between the actual and desired velocities in joint space. Several simplifications in the expressions yield a linear programming problem that can quickly be solved on line (Swanson, 2003).

The performance of these controllers can be compared in many ways. Figure 10 and Figure 11 compare the last two controllers in a situation with large initial error and the convergence appears much better for the optimal controller. For our test subjects, however, there was not a large initial error and the two performed comparably as shown in Figure 6.

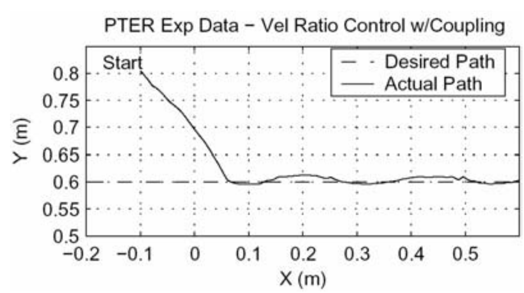


Figure 10 Controlled Path with Large Initial Error, Velocity Ratio with Coupling

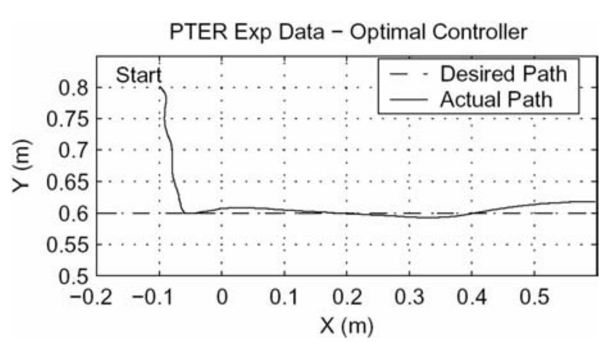


Figure 11 Controlled Path with Large Initial Error, Optimal Controller

*2.4 Evaluation of Passive Haptics*

Passive haptics and related robotic devices have a budding future. There are many issues regarding mechanical design and control yet to be resolved, however. There is an advantage of simplicity with these dissipative devices that compliments the safe behavior. Replacing the friction clutches used in PTER with magnetorheological clutches shows great promise, and a version of such a device is now being designed. These clutches have faster response, a more compact construction and avoid the discontinuity between static and dynamic friction behaviors that we have fought with our current device. The nonholonomic Cobot devices show advantages in some respects but do have complex mechanical designs in some implementations. For path following they seem by nature more appropriate, but for creating unconstrained user controlled areas complemented by restricted areas it seems this natural advantage is lost. Little has been done in the way of achieving a broader range of haptic effects with any of these devices as would be desired if they were to be used to command remote degrees of freedom.

## 3.0 TELEOPERATION WITH TIME DELAY

A major reason for human interaction with a robotic device is to transmit the human directed motion over a distance. In turn, transmission of the resulting forces back to the human (force reflection) greatly enhances the ability of the human to intelligently proceed with the given task. Transmission over substantial distances results in destabilizing time delays. This was until recently a concern primarily of space operations and other exotic activities, but with the expansion of the Internet, high-speed data communications to any point on the globe are commonplace. The Internet additionally introduces a substantial variation in the time delay. The powerful combination of the Internet and force reflecting teleoperation can only be useful if the destabilizing effects of time delay can be overcome.

*3.1 Wave Variable Transformations*

When viewed from an energy perspective, the destabilizing effects of time delay is equivalent to energy increases associated with a phase shift of the feedback loop. To address this problem (Anderson and Spong, 1989) introduced the wave variable transformation into the loop. This transformation is shown in block diagram form for a single variable in Figure 12. From a power or energy point of view

$$P = \dot{\theta}^T \tau = \frac{1}{2} u^T u - \frac{1}{2} v^T v$$

Thus a delay in the return signal *v* does not add energy to the system, since both *v* and *u* are squared in the power expression and a delay in *v* will not change the sign whereas the product of velocity and delayed torque will.

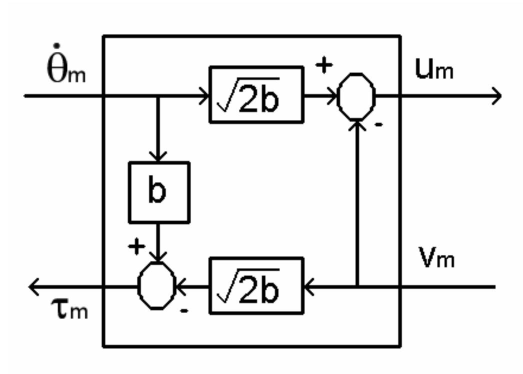


Figure 12 Wave Variable Transformation.

Unfortunately, the use of wave variables alone results in stable but poor performance. Delay can also be treated with an old technique called a Smith predictor. (Smith, 1957). This concept has its own problems in that it requires a precise knowledge of the time delay. Munir (Munir, 2001; Munir and Book, 2002) has merged these two concepts, also incorporating a state observer, to vastly improve the response in addition to stabilizing the behavior.

To present the total algorithm is beyond the scope of this paper, but one can appreciate its components from the block diagram in Figure 13.

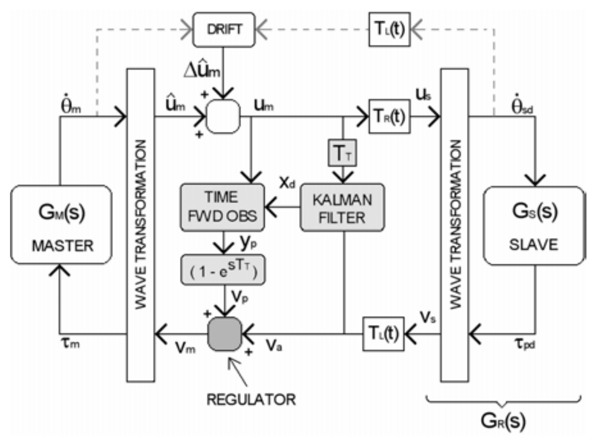


Figure 13 Prediction with wave variables for variable time delay.

To appreciate the improvement in performance one can compare to the unmodified PD control and to wave variables alone. Experiments were done over the Internet with UDP messages sent to Tokyo and reflected to control a slave simulation in Atlanta. The master was a 2-dof custom arm in the laboratory and the total delay was typically above 350ms. UDP protocol lost a fraction of the messages without adverse consequences. As shown in Figure 14 the behavior is unstable without some form of correction. With wave variables alone the system is stable but has poor response with many oscillations as shown in Figure 15. Figure 16 shows the wave variable and prediction configured for a variable time delay.

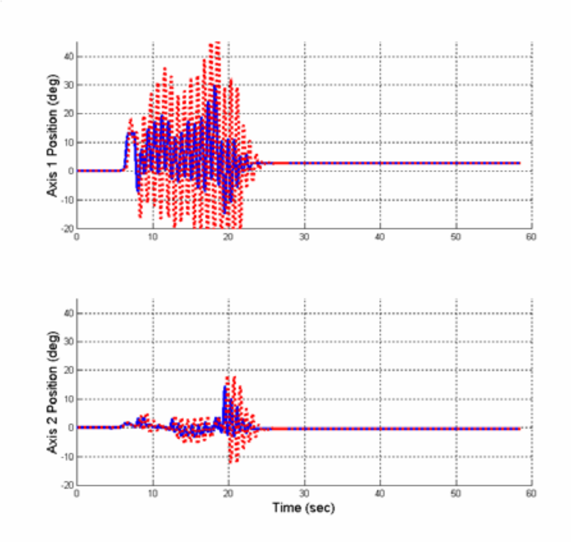


Figure 14 Unmodified Control with Time Delay

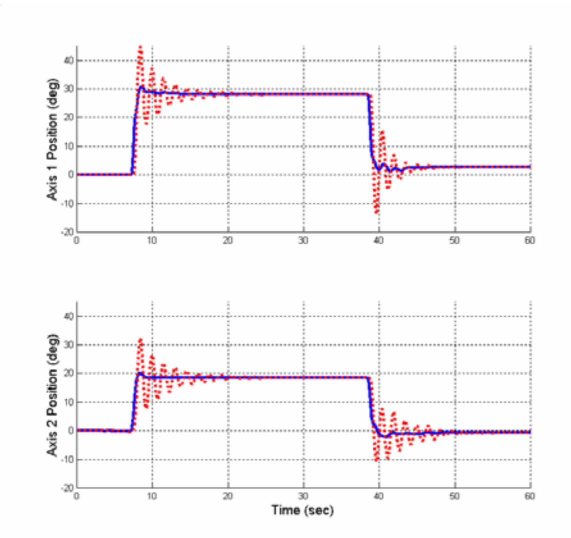


Figure 15 Wave variables with Time Delay.

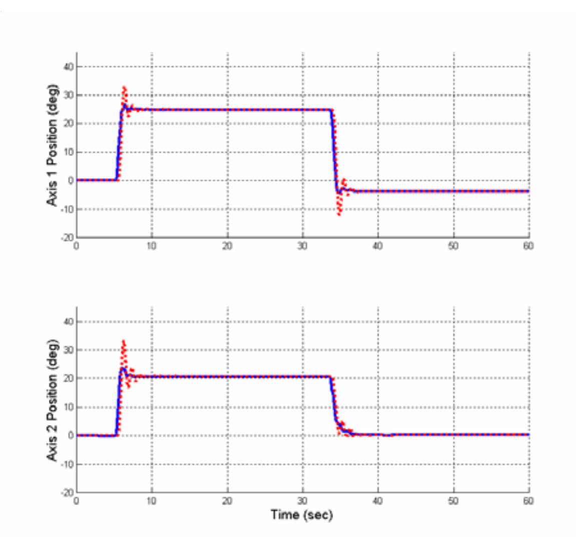


Figure 16 Control with wave variable prediction and time delay.

## 4.0 TELEOPERATION OF STANDARD EQUIPMENT

It has been usual to teleoperate manipulator arms especially designed for the role of remote operation. The high performance components used in their design is prohibitively expensive for many applications and even impossible for some large-scale systems. We should strive to make operator interfaces that enhance user effectiveness when applied to standard equipment with cost effective design. "Remote" in this case may mean at the other end of a vehicle instead of in space. Research in these areas is appearing and will begin to have a practical impact. (Krishnaswamy and Li, 2002; Kontz and Book, 2002). Laboratory work on a forklift type vehicle shown in Figure 17 has shown the advantages of haptic cues for commanding motion.

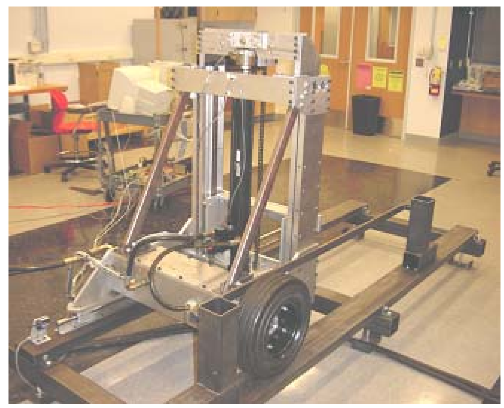

Figure 17 A haptically commanded forklift test bed.

## 5.0 SURFACE HAPTICS

In comparison to visual displays, tactile or haptic displays are extremely limited. We look at thousands of pixels with millions of colors but are forced to interact with a mouse having two or three buttons and usually no controlled feedback, or through a keyboard with around 100 keys and a binary state. A haptic manipulator will have three or six degrees of freedom. A project underway at Georgia Institute of Technology seeks to enrich the tactile modality by several orders of magnitude by making a controllable, programmable surface that will be both input and display device. Not only can shapes be displayed but also the reaction of the shapes to applied forces will be part of the interface. Since there is a separate contributed paper here (Zhu and Book, 2003), this paper will only present you with a glimpse of this project.

High resolution is sought by using MEMS technology to produce valves, sensors and inflatable cells. One prototype is the "bed of nails" roughly illustrated in Figure 18. A "deformable crust" architecture shown in Figure 19 that would allow shapes with more freedom is also under consideration. (Bosscher and Ebert-Uphoff, 2003)

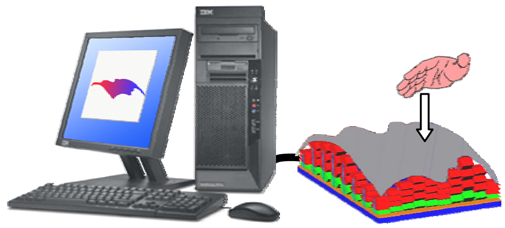

Figure 18 Digital Clay for shape input and display. Bed of nails architecture.

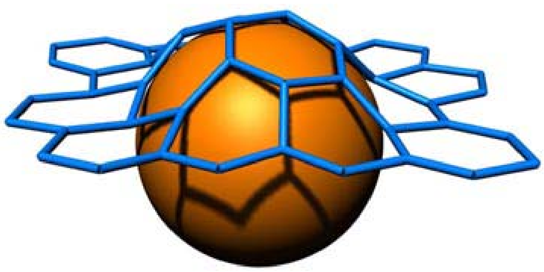

Figure 19 Deformable crust architecture for digital clay.

In both cases a large number of degrees of freedom need to be accurately controlled, requiring a distributed control of a dense nature, connected by network or bus communication.

## 5.0 CONCLUSIONS

Interaction with human users and patients is an important control consideration for robotic devices, some of which are very new (digital clay) and some of which date back to the origins of the field of robotics (teleoperation). New technology is both the source of the need and the means to meet that need. New applications will undoubtedly result and potentially have impacts as great as any in the area of robotics. Regardless of this prediction, it is an area for exciting exploration.

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